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BEAMS AT 3000 MC

Alfred Zacharias and Louis D. Smullin

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Abstract

Noise measurements were made in a demountable system, on the electron beam produced by a new type of low-noise electron gun. The purpose of the investigation was to determine the effect of the dc electric field at the cathode on Haus' noise parameters S and Π .

The noise parameter S was found to be significantly influenced by the shape of the electric field in the vicinity of the cathode. Variation of S by a factor of 2 was observed at constant beam current, and by a factor of 4.5 when the beam current was changed. Measured values for Π/S were small, the largest being 0.16. The value of Π/S was generally not found to be greatly affected by variations in the electric field at the cathode surface. However, a significantly large negative value of Π/S was produced by a field configuration that caused higher than normal cathode current density.

Agreement was not found between the noise figures predicted from the minimum-noise-figure equation, $F_{\min} = 1 + (S - \Pi) \frac{2\pi}{kT}$, and the noise figures observed in traveling-wave tubes that use this type of electron gun. Our measured values of S and Π predict a beam noisiness of approximately 3.5 times that observed in carefully processed, sealed-off tubes. The oxide-cathode coating resistance is proposed as a possible cause for this increased noisiness. Contaminants present in the vacuum of the measuring apparatus probably increased the coating resistance by decreasing the cathode activation. Data on coating resistivity, at frequencies near 3000 mc, were used to calculate the effect of cathode resistance on beam noise. The effect appears to be significant.

The effect of cathode temperature on the noise parameters was examined. It was found that S was increased by nearly a factor of 2 by an increase of cathode temperature of 80°C (approximately 10 per cent), while the value of Π/S remained unchanged.

I. INTRODUCTION

1.1 THE SOURCE OF NOISE IN BEAM TYPES OF MICROWAVE TUBES

The usefulness of a device for the amplification of weak signals is limited by the noise power output inherent in the device itself. In a beam type of microwave amplifier, the main source of noise is the electron beam. The problem of producing a more sensitive beam amplifier is thus reduced to that of producing an electron beam that will result in less noise output for a given amplifier gain.

1.2 PAST INVESTIGATION OF NOISE IN ELECTRON BEAMS

One of the earliest observations of noise in a drifting beam was made by Cutler and Quate (1). Their experiment consisted of passing an electron beam through a re-entrant cavity and measuring the noise output produced by the beam. Since a short-gap cavity is sensitive to the current modulation of the electron beam at the position of the gap, their measurement determined the noise current standing wave on the beam. A previous analysis by Pierce (2) had predicted a noise current standing wave whose ratio should be infinite, and whose minima should be zero. Cutler and Quate found nonzero minima and a standing-wave ratio (SWR) of approximately 10 db. However, they assumed that the finite minima were caused by interception noise (3). Further experiments by Rowe (4), Muehe (5), and Fried (6) were made with interception below 0.1 per cent, but finite standing-wave ratios were still observed. Watkins (7) modified Pierce's analysis and assumed that both current and velocity fluctuations were present in the beam just beyond the potential minimum. He then showed that a finite SWR of noise current would be present on such a drifting beam.

Haus (8) made a general analysis of the noise behavior of an electron beam. He showed that two parameters, S and Π , could be defined that are invariant to any linear transformation such as, for example, a change in beam velocity, which does not involve addition or subtraction of real electromagnetic power from the beam. He then showed that the minimum obtainable noise figure for a longitudinal-beam amplifier was determined by only these two parameters:

$$\left. \begin{aligned} F_{\min} &= 1 + \frac{2\pi}{kT} (S - \Pi) \\ T &= \text{room temperature} \end{aligned} \right\} \quad (1)$$

One assumption of Haus' theory was the single-velocity condition. Under this assumption, all electrons at a given beam cross section are assumed to be moving at the same velocity. This is a good approximation to make for a real beam when the average energy is greater than 2-3 volts because the velocity spread is caused by a thermionic emitter having an equivalent energy of approximately 0.1 volt. For real beams, the noise parameters will be invariant everywhere except in the immediate

vicinity of the cathode. Therefore, it is in the vicinity of the cathode that the minimum obtainable noise figure will be determined.

Some of the earliest measurements on S and Π were made by Bers (9). The electron guns on which his measurements were conducted were of a type used in low-noise traveling-wave tubes (10). His method of measuring S was to find the minimum and maximum of the noise current SWR, and then to use a relation derived by Haus (8) for a drifting electron beam.

$$S^2 = Z_o^2 \Psi_{\max} \Psi_{\min} \quad (2)$$

where $Z_o = (2V_o/I_o)(\lambda_e/\lambda_q)$ is the characteristic beam impedance, and Ψ is the self-power density spectrum of the noise current on the beam.

The values of Ψ_{\max} and Ψ_{\min} were obtained by moving a single cavity along the beam and recording its noise output. Bers also devised a method for measuring Π/S by using a resonant cavity that absorbed real electromagnetic power from the beam. The beam emerging from this cavity had a different value of S and a different noise current SWR from the beam entering the cavity. From these differences he was able to calculate the value of Π/S for the entering beam. He found values for Π/S of from 0.3 to 0.4, and values for S ranging around 9×10^{-21} watt-second.

Connor (11) essentially duplicated Bers' results with a different technique. He was able to move a probing cavity that was followed by a traveling-wave helix along the beam. The cavity measured the noise current VSWR, and thus determined S . By adjusting the helix position along the beam to yield the lowest noise figure, he was able to find F_{\min} . Hence, from Eq. 1 he could determine Π/S .

Saito (12) devised another method for obtaining Π/S , which did not require knowledge of the value of S . He used a pair of cavities, separated by a quarter space-charge wavelength, whose outputs were separately attenuated and delayed and then added in a hybrid tee. By suitable adjustments of the attenuators and phase shifters, the output of the hybrid tee can be made proportional to either the fast-wave or slow-wave excitation on the beam. From the ratio of the slow-wave output to the fast-wave output from the beam noise, Saito calculated the value of Π/S . From measurements on guns of a type similar to that used by Bers, Saito found values of S ranging around 9×10^{-21} watt-second, and values of Π/S of from 0.2 to 0.3 under normal operating conditions.

Siegman (13) calculated the values for S and Π produced by a space-charge-limited diode of planar geometry by the use of a linearized density function equation. Computations based on Siegman's analysis (14) show that S decreases to approximately 0.7 times its value at the potential minimum when the average energy of the beam is 0.5 volt above the potential minimum. Similarly, Π/S increases from its assumed value of zero at the potential minimum to approximately 0.3 at 0.5 volt above the potential minimum. Beyond 0.5 volt no change occurs, which is in agreement with Haus' theory, since the single-velocity assumption becomes valid at the higher beam voltages.

1.3 DEVELOPMENT OF LOW-NOISE GUNS

Watkins (7) devised a scheme, based on Pierce's (2) analysis, for producing a lower noise figure for a traveling-wave tube. Since Pierce's analysis predicted an infinite SWR for the noise current on a drifting beam, the use of a velocity-jump amplifier with gain less than unity ought to reduce the noise figure of a traveling-wave tube. Watkins' scheme was to use such a velocity jump before the helix, and with it he produced a traveling-wave tube having a noise figure of approximately 10 db. Muehe (5) investigated the action of the velocity jump on the SWR of the noise current in a beam. He found that the jump did decrease the maxima, but it increased the minima in exactly the same proportion. To obtain the noise figure given by Eq. 1, the phase and amplitude of the noise current SWR must be adjusted to an optimum value which is determined by the characteristics of the amplifier (8).

Peter (10) made a low-noise gun that incorporated two electrodes beyond the first anode. These electrodes divided the gun into three regions. By varying the potential on the second, or jump, electrode, the SWR of the noise current could be adjusted over a rather wide range (6, 9, 12). The best noise figure produced by traveling-wave tubes with these guns was approximately 5 db.

Currie and Forster (15) designed a hollow-beam gun which was used in a backward-wave amplifier. The novel feature of this gun was the geometry of the region near the cathode, which will be taken up in greater detail subsequently. Caulton and St. John (16) scaled Currie's hollow-beam gun to a button-cathode type of gun and used it in a forward traveling-wave tube. Both Currie's and St. John's tubes achieved a noise figure of approximately 3.5 db.

This report describes noise measurements made on St. John's guns, which were given to us for this purpose by Bell Telephone Laboratories, Incorporated.

II. MEASURING APPARATUS

The electron gun to be tested is mounted in the apparatus as shown in Fig. 1. The beam drifts through the three re-entrant cavities; one cavity is fixed to the electron-gun mounting and the other two are movable over a distance of approximately 20 cm. The electron gun and the beam are immersed in an axial magnetic field that serves to confine the beam. The electron beam is collected in a deep, magnetically shielded collector electrode. The collector is operated at a potential approximately 60 volts above the drift-tube potential. This fact and the magnetic shielding of the collector prevent secondary electrons from re-entering the drift region. A 4-inch oil diffusion pump, followed by a mechanically refrigerated trap and a liquid-nitrogen trap, maintains a vacuum of approximately 2×10^{-7} mm Hg.

The noise-detection apparatus is also shown in Fig. 1. The cavity output is fed to the precision attenuator, and then through the modulating wheel of the radiometer (17). The wheel (rotating attenuator) modulates the signal noise at 30 cps. The modulated signal is then fed to a balanced crystal mixer and converted to 30 mc. The i-f amplifier output is detected by a crystal diode whose output is then fed to a synchronous detector. Here, the second-detector output is multiplied by a reference signal from the modulator wheel and the product is averaged in a circuit with a time constant of approximately 10 seconds. This average is therefore proportional to the signal noise that is being fed to the modulator wheel. A ferrite isolator is used between the balanced mixer and the wheel for the purpose of preventing local-oscillator power from being reflected from the wheel and producing a 30-cps modulation of the mixer noise. The isolator allows a much greater sensitivity to be achieved by the radiometer.

The synchronous detector output is a dc signal that is fed to a recording microammeter. The radiometer is calibrated against a fixed noise source, a fluorescent lamp in a waveguide (17), and a precision attenuator. The lamp and its mounting have an equivalent noise temperature that is 15 db above room temperature, and a spectrum that is much wider than the receiver bandwidth.

The output from the pickup cavity is fed to the radiometer, and the precision attenuator is set to give a convenient reading on the recording microammeter. The recorder chart is set in motion, and the cavity is moved along the beam by means of a nut and lead screw arrangement driven by a synchronous motor (6). This procedure causes the standing wave of the beam noise current to be traced by the recorder. After a maximum and a minimum have been obtained, the cavity is returned to the position closest the electron gun, and the system is calibrated by either using a temperature-limited beam to produce full shot-noise modulation or passing the beam through a fine-mesh screen, in order to produce a known amount of partition noise. The screen is mounted on a vane that can be rotated into the beam at a position less than 1 cm (short compared with $\lambda_q \approx 20$ cm) from the pickup-cavity gap. The calibration produced by this screen was within 1 db of the calibration produced by temperature-limiting the beam.

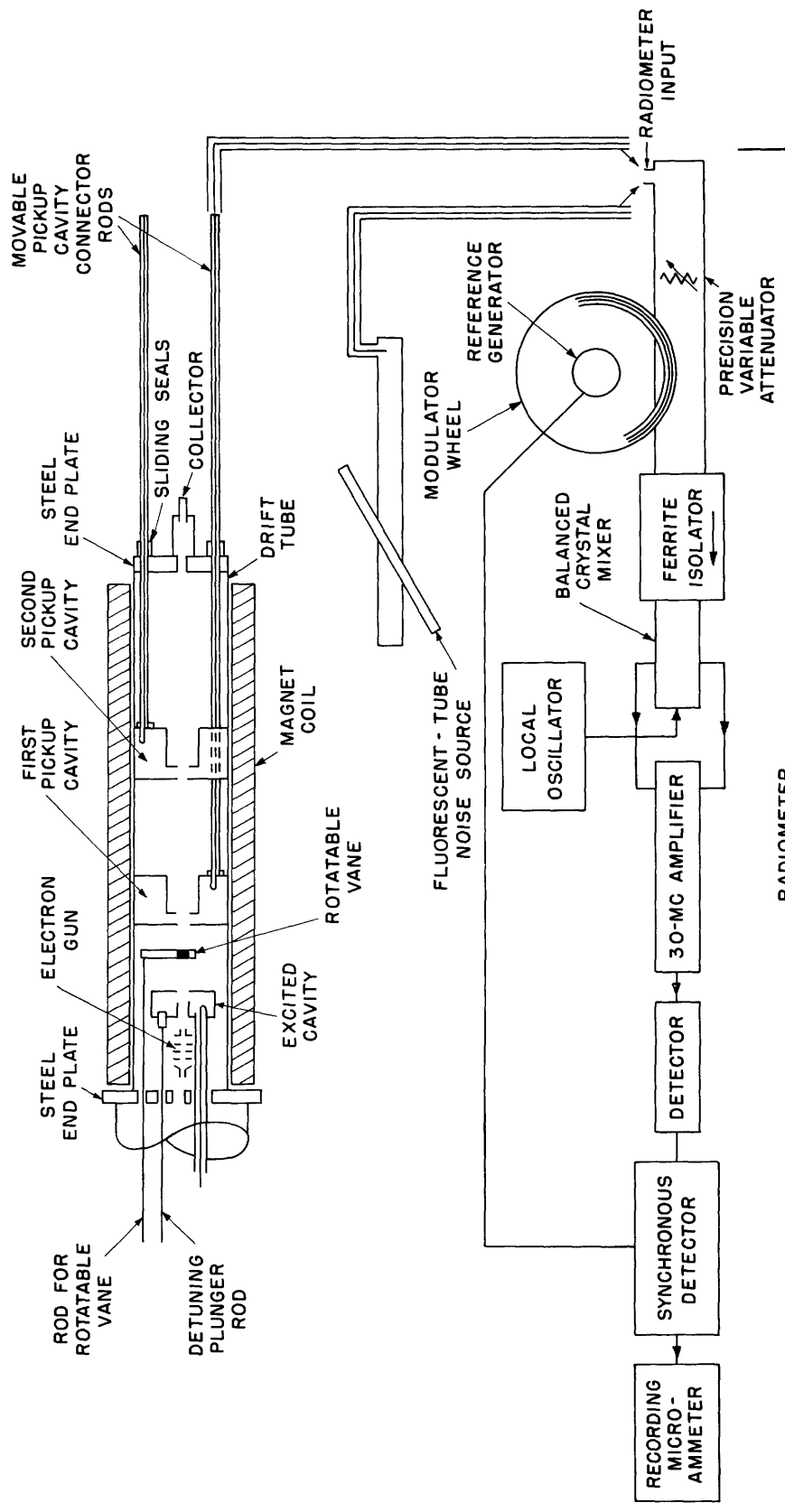


Fig. 1. Noise-detection apparatus.

2.1 THE MEASUREMENT OF S

From Eq. 2, the value of S can be computed if the values of Ψ_{\max} and Ψ_{\min} are determined. Let us write

$$(\Psi_{\max} \Psi_{\min})^{1/2} = \Psi_e = \frac{eI_e}{2\pi} \quad (3)$$

where I_e is an equivalent dc beam current that has full shot noise. Thus I_e represents a value of full-shot-noise beam current that would produce the same average noise output from the movable cavity as is produced by the actual beam of current, I_o . The ratio

$$a = \frac{I_e}{I_o} \quad (4)$$

thus represents an equivalent reduction in beam noise current below full shot noise. If we assume that the value of a is known, then

$$S = \frac{eV_o}{\pi} \frac{\lambda_e}{\lambda_q} a \quad (5)$$

To determine S, we must determine the minimum and maximum noise-power outputs of a cavity as it is moved along the beam. The geometric mean of these two powers is compared with the noise induced by a current I_o carrying full shot noise.

2.2 USE OF SAITO'S SELECTIVE BEAM COUPLER FOR MEASURING Π/S

Haus (8) showed that Π represents the real kinetic noise power of the electron beam. By using this concept, Π can be measured directly if means are available for obtaining the separate noise amplitudes of the fast and slow waves. By using a pair of cavities, Saito (12) devised an apparatus whose output is proportional to either the fast-wave or slow-wave excitation. A summary of the characteristics of this device will be given

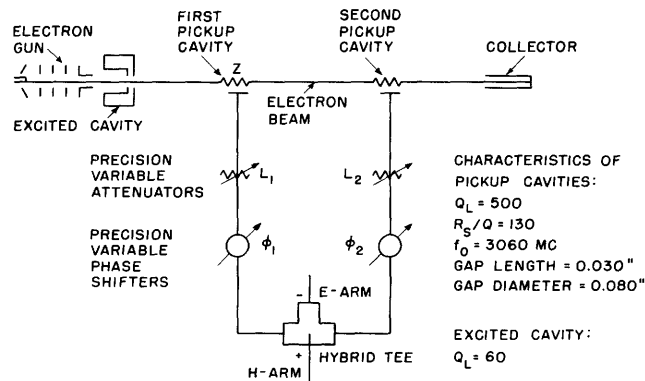


Fig. 2. Selective beam coupler.

here; a more complete treatment has been given by Saito (12).

A schematic diagram of the selective beam coupler and its associated equipment is shown in Fig. 2. The device is basically a pair of cavities whose gaps are separated by a quarter space-charge wavelength ($\lambda_q/4$). Over this distance, the fast and slow waves separate by 180° in relative phase. If the effect of the impedance of the first cavity is neglected here, then the selective properties of the coupler may be easily deduced. The excitation, and hence the output, of the first cavity will be caused by both the fast-wave and slow-wave excitations of the beam.

Consider the effect of the fast wave only on the coupler. If the output of the first cavity is used as a reference, the output of the second cavity will be delayed by an angle ϕ_{fw} , given by

$$\phi_{fw} = (\beta_e - \beta_q) \ell \quad (6)$$

where $\beta_e = \omega/\mu_o$, $\beta_q = \omega_q/\mu_o$, and ℓ is the distance between cavities. If $\beta_q \ell = \beta_q \frac{\lambda_q}{4} - \frac{\pi}{2}$, we have the phase delay of the fast wave of the second cavity

$$\phi_{fw} = \beta_e \frac{\lambda_q}{4} - \frac{\pi}{2} \quad (7)$$

Similarly, the phase delay for the slow-wave excitation will be

$$\phi_{sw} = \beta_e \frac{\lambda_q}{4} + \frac{\pi}{2} \quad (8)$$

Thus if we delay the output of the first cavity by ϕ_{fw} , and then add this signal to the output from the second cavity, we see that the signals arising from the fast-wave excitation will be in phase, but the outputs from the slow-wave excitation will be 180° out of phase. Thus for the phase-shifter settings (Fig. 2),

$$\phi_1 - \phi_2 = \phi_{fw} \quad (9)$$

the H-arm output of the hybrid tee is proportional only to the fast wave, and if

$$\phi_1 - \phi_2 = \phi_{sw} \quad (10)$$

the H-arm output is proportional only to the slow wave.

The finite impedance of the first cavity introduces a discontinuity in the kinetic voltage at the first cavity gap. In the drift space between gaps, this velocity modulation causes a current modulation to exist at the second gap which is different from the modulation that would exist without the presence of the first-cavity impedance. By use of attenuators L_1 and L_2 , we can compensate exactly for the presence of this impedance. The coupler selectivity can thus be made infinite at the resonant frequency of the cavities.

In fact, the cavities are excited by beam noise, and hence are excited over their entire bandwidths. This results in a finite selectivity that causes a periodic variation

in the output of the coupler as the cavities are moved along the beam. Saito shows that the effect of this finite selectivity can be eliminated by taking the arithmetic average between the maximum and minimum coupler outputs.

To calibrate the coupler, a third cavity is used – the excited cavity. This is an immovable, low-Q, short-gap cavity, capable of exciting the beam with a noise spectrum that is much wider than the response of the pickup cavities. Since the excited cavity has a short gap, it can introduce (almost) no real kinetic power into the beam, and therefore the ratio of fast-wave to slow-wave amplitudes on the excited beam is nearly unity.

$$A = \frac{A_2}{A_1} \approx 1 \quad (11)$$

where A_1 and A_2 are the self-power-density spectra of the fast and slow waves, respectively.

If the corresponding average outputs from the coupler are R_2 and R_1 , then we can define a calibration constant for the coupler, K ,

$$\frac{A_2}{A_1} = A = K \frac{R_2}{R_1} \quad (12)$$

and then for the excited beam ($A=1$),

$$K = \frac{R_1}{R_2} \quad (13)$$

With K determined, the ratio A may be found for a beam excited in any fashion by finding the ratio R_2/R_1 and using Eq. 12. With beam noise, a correction must be made for the thermal noise of the first cavity because it is not negligible in comparison with low-amplitude signals. This correction is discussed in detail by Saito (12).

When the ratio A has been determined for beam noise, the ratio Π/S is found.

$$\frac{\Pi}{S} = \frac{\rho^2 + 1}{2\rho} \frac{1 - A}{1 + A} \quad (14)$$

where ρ^2 is the SWR of the noise current on the beam.

III. SYSTEM CALIBRATION

3.1 SYSTEM CALIBRATION WITH FLUORESCENT LAMP

The fluorescent lamp is used to calibrate the system by comparing its known noise power output with the noise output of the pickup cavity.

If the lamp noise temperature is FT_0 , where T_0 is the ambient temperature, and if the transmission through the attenuator is A ($0 \leq A \leq 1$), then the equivalent noise temperature at the terminals of the precision attenuator is

$$T = (FT_0) A + (1-A) T_0 = (F-1) T_0 A + T_0 \quad (15)$$

The radiometer measures only changes in temperature from the wheel temperature, which is assumed to be at room temperature. Hence, the radiometer output will be proportional to the $(F-1) T_0 A$ term of Eq. 15, which we designate as ΔT . Dividing this by T_0 and then converting to decibels, we have

$$\frac{\Delta T}{T_0} = (F-1) A \quad (16)$$

and

$$10 \log \left(\frac{\Delta T}{T_0} \right) = 8(F-1) \text{ db} + (A) \text{ db}$$

The quantity $10 \log \left(\frac{\Delta T}{T_0} \right)$ will be referred to as "rdB." From Eq. 16, the radiometer may be calibrated directly in units of rdb by using the precision attenuator. Since $F = 15 \text{ db}$ means $F = 31.6$, $F - 1$ will correspond to 14.85 db. The noise figure of the lamp and its mount was known only within $\pm 0.2 \text{ db}$, and hence $F - 1$ was assumed to equal 15 db, in order to simplify the calibration.

3.2 SYSTEM CALIBRATION WITH PARTITION NOISE

North (3) predicted the production of excess noise in an electron beam passing through an intercepting aperture or screen. In his analysis, all electrons were assumed to have the same probability of being intercepted. In our case, to make the analysis applicable, care must be taken to provide this condition. The electron beams used in these experiments were confined by an axial magnetic field. To provide equal interception probability, the intercepting structure must be made of holes with radii smaller than the cyclotron radius at a temperature of 1100°K and a confining field of 550 gauss (the most probable cyclotron radius is 0.0008 inch). A 1000-mesh screen is thus required to produce North's interception noise. Such a screen was made from two 500-mesh screens that were crossed at 45°. A 0.001-inch diameter rod could not be passed through this screen.

If the beam incident on this screen is assumed to be completely smoothed by the virtual cathode, then the equivalent full shot-noise current leaving the screen is given by

$$I_o = I_T \left(1 - \frac{I_T}{I_K} \right) \quad (17)$$

where I_T is the transmitted current, and I_K is the incident current.

Thus we have a beam with known noise current entering the cavity, and we have a means of calibrating the noise output of the cavity without knowing the gap coupling coefficient specifically.

3.3 SYSTEM CALIBRATION IN TERMS OF KLYSTRON GAIN MEASUREMENT

The actual noise power delivered to the receiver by the system is dependent upon the mean-square noise current in the beam, and on the pickup cavity parameters. If these parameters were independently known, then the beam noise current could be deduced from the noise output power. It is possible to determine these parameters through a measurement of the "klystron gain" of the system.

Assume that the bandwidth of the system is Δf , and that the cavity is matched to the load. Then the cavity output caused by beam noise will be

$$P = \frac{|\bar{i}|^2 M^2 R}{2} = 4\pi\Delta f \Psi \frac{M^2 R}{2} \quad (18)$$

where M is the gap coupling coefficient for the cavity, R is the equivalent cavity-gap shunt resistance, and $|\bar{i}|^2$ is the mean-square beam-noise current resistance at the position of the gap.

For full shot noise,

$$|\bar{i}|^2 = 2eI_o\Delta f \quad \text{and} \quad \Psi = \frac{eI_o}{2\pi} \quad (19)$$

The product $M^2 R$ can be determined by providing in the system a second cavity with characteristics identical to those of the first cavity. [Such a cavity is also required by Saito's coupler (12).] When the gaps of the two cavities are separated by a quarter space-charge wavelength, a two-cavity klystron is created whose power gain at the resonant frequency of the cavities can be shown (9) to be

$$G = \frac{M^4 R^2}{Z_o^2} = r^2 \quad (20)$$

This gain can be easily measured by using a signal generator and the receiver of the radiometer, with an oscilloscope substituted for the synchronous detector. The precision attenuator is used for the gain measurement.

If the receiver bandwidth is assumed to be much narrower than the cavity bandwidth, the following calculation can be performed. Full shot noise, for the dc beam current I_o , is assumed to pass through the cavity gap. The increase above thermal-noise output

in the cavity-output noise can be written as a power-density-spectrum amplitude which is given by

$$U_c = \Psi_{\text{FSN}} \frac{rZ_o}{2} = \frac{eV_o}{2\pi} \frac{\lambda_e}{\lambda_q} r \quad (21)$$

The thermal-noise spectrum from the cavity, in the absence of the beam, is given by

$$U = \frac{kT}{2\pi} \quad (22)$$

The ratio U_c/U yields the rdb output from the cavity, provided that the cavity is matched to the radiometer, and that the receiver bandwidth is much narrower than that of the cavity. Hence

$$\text{rdb (full shot noise)} = 10 \log \left(\frac{eV_o}{kT} \frac{\lambda_e}{\lambda_q} r \right) \quad (23)$$

IV. THE ELECTRON GUN

The electron guns used for these experiments were produced by Bell Telephone Laboratories, Incorporated for use in a low-noise traveling-wave tube operating at S-band. A cross-section view of this gun, together with some approximate dimensions pertinent to our work, is shown in Fig. 3. The gun is a solid-cathode scaling (16) of a hollow-cathode design first proposed by Currie and Forster (15). The gun consists of two sections: (a) first-anode, cathode, and beam-forming electrode; and (b) anodes 2, 3, and 4 which constitute a noise transducer (10) that allows variation of the SWR of the beam-noise current in both phase and magnitude. Section (b) is assumed to be a lossless beam

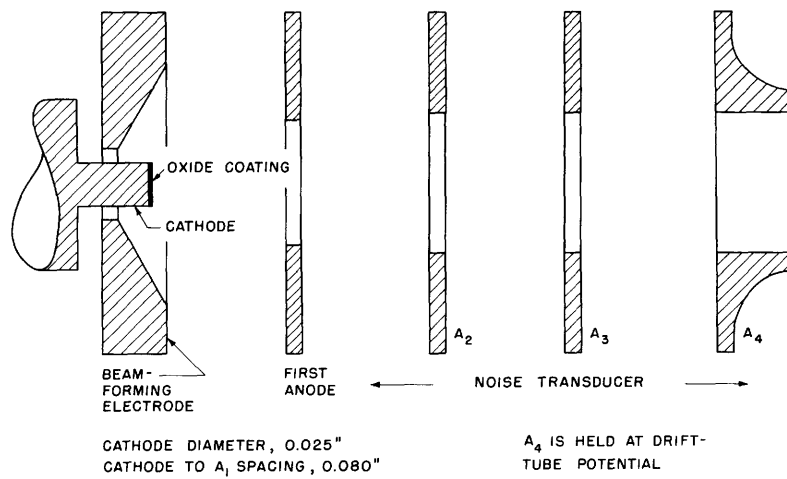


Fig. 3. The BTL low-noise gun.

transducer, and the noise parameters S and Π/S are determined by section (a). In our measurements, the noise transducer is used to reduce the magnitude of the SWR of noise current so that the minima will be readable and not obscured by higher-order space-charge modes that have greater space-charge wavelengths than the lowest-order mode.

Currie and Forster (15) have described some measurements made on their hollow-beam prototype for the BTL gun. They used their gun in a backward-wave amplifier, and found that the noise figure of this device was profoundly influenced by the voltages applied to A_1 and to the beam-forming electrode (Fig. 3), while the beam current was kept constant. They found a minimum for the noise figure in a plot of noise figure against V_{BFE} (the beam-forming-electrode voltage), with V_1 (the A_1 voltage) adjusted to keep the beam current constant. The noise transducer was continuously adjusted so that the noise figure obtained was always the minimum available noise figure.

Currie and Forster examined the potential profiles for the geometry of their gun in an electrolytic tank. They found that with V_{BFE} approximately 12 volts above the cathode, and with V_1 3 volts above the cathode, a potential profile that had two very distinct

features was produced. The potential gradient at the circumference of the cathode was an order of magnitude greater than the gradient at the center of the cathode. Also, the gradient at the edge was largely radial. This led to the prediction of the formation of a hollow beam from their cathode that was already hollow, that is, two concentric cylindrical sheets of current, one inside the other. Measurements, which they describe, show that this prediction was correct.

The second feature of the potential profile was an extended region of low potential gradient along the cylindrical surface, extending from the circumference of the cathode. Using injected current to simulate space charge in their electrolytic-tank measurement, Currie and Forster obtained the potential profile for the region traversed by the beam. They found that the emitted electrons would travel with very low velocities for a much greater distance than they would have traveled in the potential distribution between a parallel-plane emitter and anode, with current density identical to that present in their cylindrical beam.

The minimum noise figures obtained by Currie and Forster in their backward-wave amplifier, and at Bell Telephone Laboratories in a forward-wave amplifier with a solid cathode, were both between 3 db and 3.5 db. The noise figure of the RCA traveling-wave tubes, whose guns were tested by Saito (12), was from 4.5 db to 5.5 db.

The present experiments were performed to determine the effect on the noise parameters of variation in the electric-field configuration around the cathode. This was accomplished by measuring S and Π/S , as described in sections 2.1 and 2.2, for various values of V_{BFE} and V_1 , which were chosen so that the beam current was kept constant.

4.1 MEASUREMENTS ON THE BTL GUN NO. 1

The gun was installed in the measuring apparatus, the system was evacuated to a pressure of approximately 2×10^{-7} mm Hg, and the cathode was activated, following a schedule provided by Bell Telephone Laboratories. A 200- μ a beam was then established, and five sets of electrode voltages were determined, each of which produced a 200- μ a beam current and a noise-current SWR of less than 6 db. These conditions are listed in Table 1. The drift-tube potential was fixed at 500 volts; this resulted in a space-charge wavelength of $20.6 \text{ cm} \pm 0.2 \text{ cm}$ for all five sets of electrode voltages. This invariance of space-charge wavelength allowed one set of adjustments for the phase shifters and attenuators to be used for the selective beam coupler. With the cavity-gap separation set at 5.13 cm ($\lambda_q/4$), the two-cavity-klystron gain was constant at 0.12 for all five sets of electrode voltages.

The first cavity was calibrated by rotating the fine-mesh screen into the beam approximately 0.5 cm in front of the first cavity gap. The screen transmission is measured by the collector current; the collector current when the screen is not intercepting gives the cathode current. Equation 17 is used to obtain the dc current that produces full shot noise at the first cavity gap. The noise output caused by this dc current

is then measured. Linear extrapolation to the full-shot-noise output at 200- μ a beam current yields the final calibration needed to calculate S by Eq. 5. The calibration remained constant within 0.2 db for all 5 gun conditions.

The space-charge wavelength was found by feeding a sinusoidal signal into the excited cavity and measuring the distance between successive minima of the first-cavity output.

The constant K , from Eq. 13, was found by noise-modulating the beam with the excited cavity, and using the ratio of the fast-wave to the slow-wave coupler outputs thus obtained.

With the external noise modulation removed, and the excited cavity detuned, the calibrated coupler was then used to measure the ratio of slow-wave to fast-wave noise excitation on the beam. Then, by using the output from the first cavity only, the noise-current standing wave was determined. This measurement provides the value of ρ^2 that is needed for Eq. 14, and also enables the determination of the value of S by making use of the first-cavity shot-noise calibration previously determined, and Eq. 5.

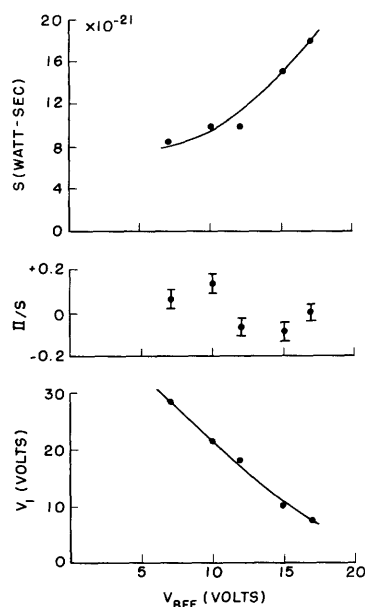


Fig. 4. Variation of S and Π/S on BTL gun No. 1 at 200- μ a beam current.

The values of S and Π/S thus obtained are tabulated in Table 1, and plotted in Fig. 4. Figure 4 illustrates the large variation in S that is obtained by varying V_{BFE} and V_1 . From a consideration of the experimental errors involved in determining A (Eq. 11), the probable error in Π/S is estimated to be ± 0.05 . No correction was made for the thermal noise of the first cavity, since the correction is within this error, and the values of Π/S are so close to zero that the correction will not have a significant effect on $(1-\Pi/S)$. The variation produced in $(1-\Pi/S)$ by variation of V_{BFE} is, therefore, much less than the change produced in S .

The beam current usually drawn from this gun is considerably below the 200 μ a used in the measurements just described.

Thus a measurement was made at 75- μ a beam current, which is the average used in the BTL amplifiers. The measurement was made at only one set of electrode voltages. The value chosen for V_{BFE} was +10 volts because this appeared to give the largest value of Π/S at 200 μ a. Because the space-charge wavelength became too large for the drift tube, the drift potential was decreased to 350 volts. The value of λ_q was 22.5 ± 0.2 cm. The first cavity was again calibrated with the use of the fine-mesh screen. The selective beam coupler was readjusted for maximum selectivity under the new conditions. The

Table 1. Data on BTL Gun No. 1.

(For $I_k = 200 \mu\text{a}$; interception below $0.05 \mu\text{a}$; drift voltage, 500 v; $\lambda_q = 20.6 \text{ cm}$; $r = 0.35$)

V_{BFE} (volts)	V_1 (volts)	V_2 (volts)	V_3 (volts)	ρ^2 (db)	Mean Output (db below shot noise)	S (watt-sec)	Π/S
7.1	28.2	104	93	3.2	18.2	8.4×10^{-21}	+ .06
10.0	21.5	84	71	3.9	17.8	9.7×10^{-21}	+ .13
12.0	18.5	98	87	4.7	17.4	9.9×10^{-21}	- .07
15.0	10.3	52	105	5.3	15.6	15.3×10^{-21}	0
17.0	7.5	40	105	6.0	14.9	14.9×10^{-21}	- .09

(For $I_k = 75 \mu\text{a}$; interception below $0.02 \mu\text{a}$; drift voltage, 350 v; $\lambda_q = 22.5 \text{ cm}$; $r = 0.16$)

V_{BFE} (volts)	V_1 (volts)	V_2 (volts)	V_3 (volts)	ρ^2 (db)	Mean Output (db below shot noise)	S (watt-sec)	Π/S
10.0	5.4	38	27	2.7	19.0	3.8×10^{-21}	+ .16

Table 2. Data on BTL Gun No. 2.

(For $I_k = 75 \mu\text{a}$; interception below $.02 \mu\text{a}$; drift voltage, 350 v; $\lambda_q = 24.3$; $r = 0.18$)

V_{BFE} (volts)	V_1 (volts)	V_2 (volts)	V_3 (volts)	ρ^2 (db)	Mean Output (db below shot noise)	S (watt-sec)	Π/S
4.7	14.0	146	71	4.2	18.5	3.8×10^{-21}	- .04
7.7	8.3	38	28	2.8	19.7	2.8×10^{-21}	+ .06
9.6	3.5	38	28	3.4	19.9	2.7×10^{-21}	- .03
13.4	2.4	40	29	2.6	18.2	4.0×10^{-21}	- .04
18.3	1.8	41	30	3.4	18.6	3.7×10^{-21}	- .24

Table 3. Data on BTL Gun No. 3.

(For $I_k = 75 \mu\text{a}$; interception below $.02 \mu\text{a}$; drift voltage, 250 v; $\lambda_q = 18.8 \text{ cm}$; $r = 0.16$)

T_c (°C brightness)	V_1 (volts)	V_{BFE} (volts)	S (watt-sec)	Π/S (± .05)
810	3.0	9.0	2.6×10^{-21}	- .02
850	2.3	9.0	3.4×10^{-21}	- .08
890	1.8	9.0	4.7×10^{-21}	- .06

klystron gain was measured as 0.024, which gave a value for r of 0.16. The coupler was calibrated by feeding broadband noise into the excited cavity. The constants obtained from beam noise are listed in Table 1. The value of S was 3.8×10^{-21} watt-second, and the value of Π/S was 0.16 ± 0.05 .

Comparison with the data obtained at 200 μ a shows that a reduction of V_1 to lower the beam current to 75 μ a caused a reduction in S by a factor of 2.5 but produced no significant change in Π/S . Computing the minimum available noise figure from these values of the noise parameters, we find that $F_{\min} = 5.8$ (7.6 db), whereas the BTL amplifiers have noise figures between 3 db and 3.5 db. The gun used in our system produced approximately 4.5 times the excess noise produced by such a gun operated in a BTL amplifier. There were three factors that could have caused such a difference. First, there was the magnitude of the magnetic field. Our magnet could not produce the 1100-gauss field that the BTL amplifiers use at the gun region. The measurements were carried out at 650 gauss. It was found at Bell Telephone Laboratories that a 1-db reduction in noise figure occurred when the focusing field strength was increased from 500 gauss to 1100 gauss. This would cause the excess noise in our beam to be 1.5 times that in the BTL tubes. Second, there was the operating cathode temperature. In the BTL amplifier the cathode is operated at a temperature of approximately 630°C (brightness), but the cathode temperature that we found necessary for maintaining emission was approximately 830°C (brightness). This higher temperature would cause a higher velocity modulation to exist, and thus S would be higher. However, the increase in temperature alone should result in only a 20 per cent increase in excess noise. Third, there is the activity of the cathode. This will be discussed in section 4.5. From the magnitude of the effects of the first two factors, the activity of the cathode must be the principal reason for the greatly increased noisiness of the gun used in our system.

4.2 MEASUREMENTS ON BTL GUN NO. 2

To explore further the noise reduction characteristics of these electron guns, and partly to check the results of measurements on the first gun, BTL gun No. 1 was removed from the system and a second gun was inserted and activated.

In these measurements the beam current was held constant at 75 μ a; five sets of gun voltages, which produced a beam-noise-current SWR of less than 5 db, were determined. In four of these sets, the noise transducer voltages did not require change when V_{BFE} and V_1 were varied. However, when V_{BFE} was reduced below 5 volts, the SWR of the noise current increased to more than 8 db. Referring to Table 2, we see that a large change in transducer voltage was required to reduce the SWR to a satisfactory value.

The value of λ_q was 24.3 ± 0.2 cm for all 5 conditions. The drift potential was 350 volts. The value of r found from the klystron gain was 0.18.

The measurements of S showed a distinct minimum when they were plotted against V_{BFE} (see Fig. 5a and Table 2). The values and variation of Π/S are, again, small,

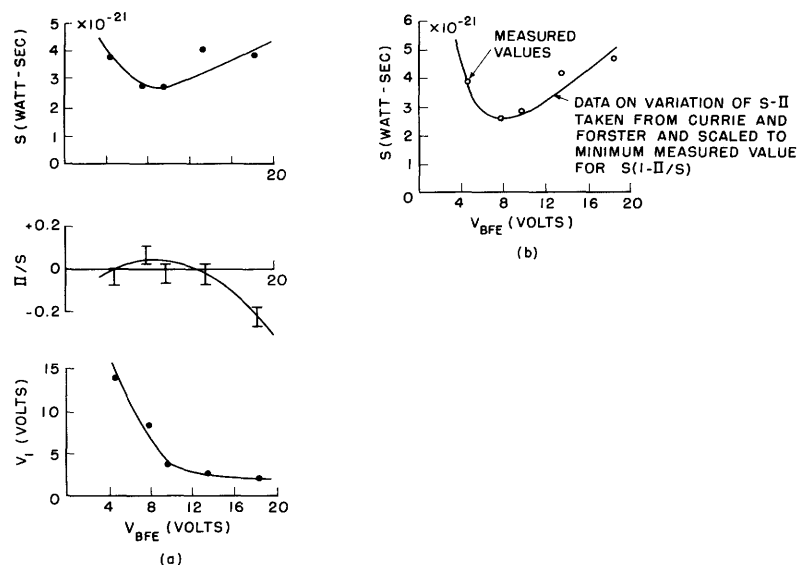


Fig. 5. Variation of S and Π/S on BTL gun No. 2 at 75- μ a beam current.

although at $V_{BFE} = 18$ volts, Π/S is definitely negative. The highest positive value of Π/S is smaller than that observed in BTL gun No. 1 at a current of 75 μ a. However, the difference in the value of $(1-\Pi/S)$ for the two guns is only 12 per cent. The difference between the minimum value of S observed in the second gun and the value of S at 75 μ a observed in the first gun is 30 per cent. The minimum available noise figure predicted from the measurements on the second gun would be 7.0 db, which is still much higher than the noise figures observed in BTL amplifiers in which this type of gun is used.

The cathode temperature of this second gun was somewhat lower than that required by the first gun for stable emission. The operating temperature was approximately 800°C (brightness). The magnetic field was 650 gauss. We are led, again, to the conclusion that cathode activity must be the reason for the greater noisiness of the BTL guns that are operated in our system.

4.3 EFFECT OF CATHODE TEMPERATURE

A third BTL gun was mounted in the system and activated. The value of V_{BFE} was chosen as +9 volts, and V_1 was varied to hold the beam current constant as the cathode temperature was increased. The data are shown in Table 3. The variation of S is very pronounced, increasing more than linearly with absolute temperature; the variation of Π/S is not significant. Since there was no opportunity to repeat this measurement on another gun, we do not know whether the rapid variation is related to the particular state of activity of the cathode or is characteristic of this type of gun. (Measurements on the Pierce gun show S proportional to cathode temperature in the space-charge-limited region.)

4.4 COMPARISON OF OUR MEASUREMENTS WITH OTHER WORK

Bers (9) and Saito (12), using electron guns produced for traveling-wave amplifiers having noise figures of 5-7 db, made measurements on S and Π/S . Bers' measurements of S were grouped around 10×10^{-21} watt-sec for oxide-coated cathodes. Saito's measurements of S were grouped around 9×10^{-21} watt-sec for oxide-coated cathodes. In all cases, the value of Π/S was higher than 0.25. The electron guns used by Bers and Saito were of different design from the guns used in these measurements. The guns that they used had fairly uniform cathode loading and did not have the large radial potential gradients at the cathode surface, which are present in the guns used in these measurements, and in the measurements by Currie and Forster (18).

Comparing our results with those of Bers and Saito, we feel that the reduction of the noise parameter $S - \Pi$ in the BTL guns is accomplished by a reduction of the S parameter, and not by an increase in Π/S .

Currie and Forster (18) measured the noise figure of a backward-wave amplifier that had a hollow-cathode version of the gun that was used. They varied the value of V_{BFE} over the same range of values, as we did for the second gun. The results of their measurement of $S - \Pi$ is drawn as a solid curve in Fig. 5b. Their minimum value of $S - \Pi$ is scaled to match our minimum measured value for $S(1-\Pi/S)$. Our measured values of $S(1-\Pi/S)$ are indicated as points. The minimum of $S - \Pi$ occurs in the range of values of V_{BFE} where the slope of the V_1 versus V_{BFE} curve undergoes an abrupt change (see Fig. 5a). Currie and Forster show, by measurements on beam density, that in this range of V_{BFE} the cathode current is taken principally from the cathode circumference. As V_{BFE} is made larger, this cathode area begins to become temperature-limited, and the beam becomes noisier. If V_{BFE} has the value that produces the minimum of $(S-\Pi)$, the radial electric field at the cathode is small, and the gun should behave similarly to previous designs.

The data obtained at 200- μ a beam current lend themselves to this explanation of the noise-reduction process. The values of V_{BFE} were the same as those used at 75 μ a; however, V_1 was greater than at 75 μ a. The plot of V_1 versus V_{BFE} (Fig. 4) shows no abrupt change in slope; this indicates that current was always being taken, in significant density, from the center of the cathode. As V_{BFE} was made greater, the edge of the cathode began to become temperature-limited, and the noise began to increase. At lower values of V_{BFE} , the noise was reduced, but not below values observed previously by Bers (9) and Saito (12). It is only when the total cathode current is reduced to the point at which the strong radial electric field can act on current emitted from space-charge-limited areas, that the noise-reducing mechanism can operate. When the current was reduced from 200 μ a to 75 μ a, the value of $S - \Pi$ decreased by a factor of 2.6.

From the data at 75- μ a beam current, the value of S undergoes a 40 per cent variation, when V_{BFE} is changed from 5 volts to 13 volts, but over the same range $(1-\Pi/S)$ changed by no more than the experimental error in this quantity, that is, approximately

± 10 per cent. As a result, we could conclude that the noise-reducing mechanism acts principally on S , and not on Π/S . In section 4.5 we shall discuss the role that cathode resistance may play in obscuring the actual behavior of the noise-reducing mechanism of these guns.

4.5 POSSIBLE EFFECT OF CATHODE RESISTANCE ON NOISE PARAMETERS

The oxide-coated cathode exhibits two forms of impedance. One form, the interface impedance, occurs at the boundary between the coating and the nickel-alloy base. This impedance is frequency-dependent, and may be characterized by a parallel combination of resistance and capacitance. The equivalent time constant of this impedance is approximately $1 \mu\text{sec}$. Consequently, its effect at microwave frequencies can be ignored. The second form, however, is caused by the finite conductivity and the permittivity of the oxide coating. Measurements by Herbst and Houldin (19) have shown that the coating conductivity is constant from dc to frequencies above 2350 mc.

If the oxide coating is very thin (actual thickness is approximately 50μ) compared with a wavelength in the coating (or the skin depth in the coating, if $\sigma \gg \omega\epsilon$) then an equivalent conductivity can be determined for the coating, and an equivalent series resistance for the coating can be determined for any frequency. The conductivity σ will be shunted by a susceptance $j\omega\epsilon$; then the series resistivity is

$$\rho_e = \frac{\sigma}{\sigma^2 + \omega^2 \epsilon^2} \quad (24)$$

At a given frequency, the maximum value for ρ_e will occur when $\sigma = \omega\epsilon$, and at this value of σ , $\rho_e = 1/2\omega\epsilon$.

Herrmann and Wagener (20) found that the coating conductivity is strongly dependent on the cathode activation. They give data on both the conductivity and the dielectric constant of the oxide coating. The value of the dielectric constant is approximately 8, which makes $\omega\epsilon$ equal to 1.3 mhos/meter at 3000 mc. Also, their value for the conductivity of fully activated coatings is approximately 0.5 mhos/meter. Thus, decreasing activity, which results in decreased conductivity, would seem to produce a lower value of ρ_e and hence to reduce the equivalent series resistance. However, Herbst and Houldin (19), in measurements on a group of planar triodes, found that $(R\omega C)^2 \ll 1$ for tubes having much higher resistivity than the average. Thus, for cathodes having average resistance, the condition must also hold. Here R was the cathode resistance shunted by the equivalent coating capacity, C . If the cathode coating can be considered uniform, then Herbst and Houldin's R and C are proportional to ρ_e and ϵ , respectively. The factors of proportionality are the coating thickness and cross-section area, so that $RC = \rho_e \epsilon$. The frequencies that they used were between 700 mc and 2500 mc. They found values of σ of 0.3-0.4 mhos/meter, which were constant over the ranges from dc to 2350 mc. The conclusion to be reached is that the capacitive shunting of the coating resistance is

much less than that which would be caused by a dielectric constant of 8 at 2500 mc. Also, the value of resistivity for well-activated cathodes appears to be considerably lower at these frequencies than the values given by Herrmann and Wagener (20) for essentially dc operation.

In order to estimate the effect of the resistivity observed by Herbst and Houldin (19), we shall choose a value for ρ_e of 0.5 ohm/meter and calculate the cathode resistance for a coating thickness of 50 μ with a surface area 1/20 that of the total cathode area. (The last figure is an estimate of the area contributing to the beam current as previously discussed.) The cathode resistance is computed as 390 ohms. This resistance will now be placed at the potential minimum, in series with the beam. The value of kinetic-voltage modulation (noise), Φ_o , just before the resistance, is assumed to be the Rack voltage (2, 8), and the current modulation Ψ_o is assumed to be full shot noise uncorrelated with Φ_o .

$$\Phi_o = \frac{(4-\pi)(kT_c)^2}{2\pi e I_o}; \quad \Psi_o = \frac{e I_o}{2\pi}$$

where T_c is cathode temperature, and I_o is dc beam current.

$$\Pi_o = \Lambda_o = 0 \tag{25}$$

Here zero subscript values refer to noise parameters before the beam passes through the cathode resistance. When the beam flows through the cathode resistance, the current modulation will not change, and Ψ_o will produce a voltage fluctuation by flowing through the series cathode resistance, R . Because of this, the output voltage and current will be correlated; the correlation will be real and negative. Using Eq. 25, we obtain the noise parameters as modified by R :

$$\left. \begin{aligned} \Phi_o &= \Phi_o + R^2 \Psi_o \\ \Psi_1 &= \Psi_o \\ \Pi_1 &= -R \Psi_o \\ \Lambda_1 &= \Lambda_o = 0 \end{aligned} \right\} \tag{26}$$

We can now compute the ratio S_1/S_o and find Π_1/S_1 . The cathode temperature is assumed to be 1100°K, and I_o is 75 μ a. We find that

$$\left. \begin{aligned} \frac{S_1}{S_o} &= 1.1 \\ \frac{\Pi_1}{S_1} &= -0.31 \end{aligned} \right\} \tag{27}$$

If, now, the value of ρ_e were to be increased by a factor of 5 so that the conductivity is approximately equal to that found by Herbst and Houldin (20) for their high-resistance cathodes, the cathode resistance would be 1950 ohms, and the results of the computations would be

$$\left. \begin{aligned} \frac{S_1}{S_0} &= 1.9 \\ \frac{\Pi_1}{S_1} &= -0.86 \end{aligned} \right\} \quad (28)$$

The value of conductivity for the results of Eqs. 27 is 2 mhos/meter, whereas the conductivity for Eqs. 28 is 0.4 mho/meter. The effective value of the dielectric constant for the coating must be less than 2 at 3000 mc and at 1100°K for the conductivity of the coating to produce the values of equivalent cathode resistance that we used, and the values measured by Herbst and Houldin (19) at approximately these frequencies.

V. CONCLUSIONS

The cathode resistances used to obtain Eqs. 27 and 28 are very small; the resulting dc potential drop at 75 μ a would only be 0.14 volt for the 1950 ohms used. However, the increase in beam noisiness caused by this resistance is a factor of 3.5, if no subsequent reduction is assumed to occur beyond the potential minimum.

The analysis by Siegman (13), and by Siegman, Watkins, and Hsieh (14), assumes full, uncorrelated shot noise at the potential minimum. In their analysis of the region beyond the potential minimum, they find that S is reduced by a factor of 0.7, and Π/S increases to +0.3. It is not apparent what changes will result from modifying the conditions at the potential minimum to allow for the presence of cathode resistance. Furthermore, it is the emitted current that is affected by the cathode resistance; the effect of the region between the cathode surface and the potential minimum has been ignored in our calculations of S_1 and Π/S_1 .

If we assume that the noise-reducing action of the multivelocitv region from the cathode surface to a potential of 0.5 volt is not critically modified by the real, negative correlation between emission velocity and current, then our calculations show that cathode resistance has a very profound effect on the noisiness of the beam.

Saito (12) made measurements of S and Π/S at reduced cathode temperature. He found that Π/S would be reduced from approximately +0.25 at operating temperature to from 0 to -0.1 at reduced temperature. His value of S was increased approximately 20 per cent by this temperature change.

The largest, negative value of Π/S obtained from measurements on BTL gun No. 2, at $V_{BFE} = +18$ volts, lends further support to the hypothesis of the effect of cathode resistance. The potential distribution at the cathode surface, with increasing V_{BFE} , causes a reduction of the cathode area contributing to emission, as we have seen. This decrease in effective cathode area will increase the cathode resistance, and thereby cause the observed negative correlation.

The data from BTL gun No. 3 indicated that (a) the simple theory of the effect of cathode resistance is incorrect, or (b) the cathode resistance is temperature-dependent, or (c) cathode resistance is not the significant effect, and hence the increased noise observed in the measurements on the first and second guns results from some other effect of poor activation.

It is clear from the measurements on the three guns that the noise-reducing mechanism of the BFE- A_1 structure serves to reduce the value of S , and does not produce a large positive correlation, Π/S .

This type of gun seems to be fundamentally different from the conventional gun that has a uniformly emitting cathode.

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